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Sensitivity Analysis and Productivity Study of *Directpipe* Technology by Using Simulation

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Abstract

Many techniques of trenchless technologies have been evolved over time to install, maintain, and manage underground infrastructure system, but all of these fail to satisfy implementer due to complex implementation process, economy, and adaptability to different geological conditions. Directpipe technology is one of new technology that has been invented by German's Herrenknecht Inc. recently. It claims that the technology is economical, fast, and has a single step installation procedure. The objective of this paper is to analyze and evaluate that claim by using CYCLONE model simulation. The simulation is used to compare the Directpipe technology with traditional trenchless technology by incorporating real costs and duration into the model. Sensitivity analysis is carried out to find out a suitable combination of resources delivering utmost productivity.

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Keywords: trenchless; micro tunnelling; horizontal directional drilling.

1. Introduction

Many techniques have been evolved over the time to install, maintain and repair underground infrastructure system. Open cut method is one of such old technology which had been used initially. But the method proved to be uneconomical, ineffective in context of developed urban area where more buried utilities being installed. Trenchless technology has been emerged as solution to open cut method. Horizontal directional drilling (HDD) and Micro tunnelling are two trenchless technology methods which have

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been used recently. These methods are successful in eliminating drawbacks of the open pipe method but they found to be limited by depth of cutting, geological layers and multistep complex installation process. So there is need for technology which can be used widely in case of different geological conditions, extend to any depth of cut and efficient over existing HDD and Micro tunnelling techniques (Bennet *et al*., 1999).

Direct Pipe technology is developed by German based tunnelling system company 'HerrenknechtInc'. Direct pipe technology combines advantages of well established two trenchless technologies one is horizontal directional drilling (HDD) and Micro tunnelling. The direct pipe method made its debut after crossing of the river Rhine in Worms Germany(Pfeff, 2008).

The purpose of this paper is to: (1) determine the productivity of the system and compare it with productivity of the system obtained in the field, (2) compare the *Directpipe* technology with conventional trenchless technologies in terms of cost, productivity, and application in context of geological pattern, depth of cutting and method of implementation, and (3) determine sensitivity of the system with respect to change in management controlled variables to achieve maximum productivity.

2. *Directpipe* Technology

On a site, the *Directpipe* method has some main elements such as cranes, pipe storage, section preparation area, welding and cutting machine, backhoes, bentonite pump and mixing tank, spoil storage tank, control office, separation unit, and water overflow tank (Pfeff, 2008).

A pipe thruster is the main elements in the *Directpipe* technology. It is setup inside launch pit. The thruster is fixed horizontally as well as vertically by using steel beams and anchors so as to transfer the thrust forces to surrounding soil. Thruster can deliver average thrust force of 15 t to maximum 28 t to the Direct Pipe machine above it. Fig. 1 shows a pipe thruster.

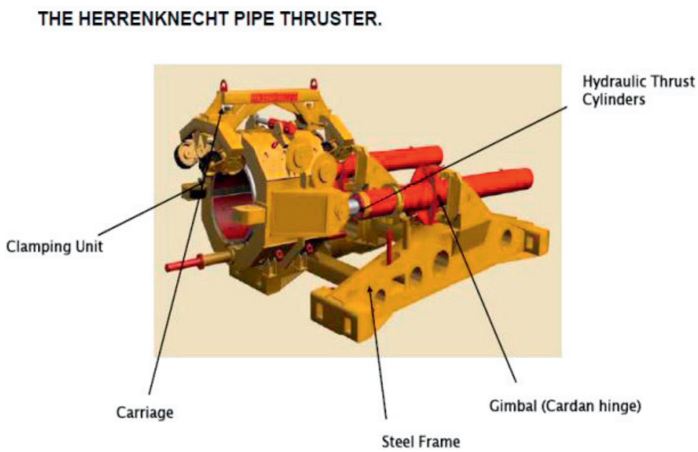

Figure 1. The Directpipe machine: Pipe Thruster

A *Directpipe* machine is mounted in front of the pipeline. The direct pipe machine and whole pipeline afterwards can be controlled by using two active steering joints. A thruster provides thrust to the direct pipe machine as well as pipeline and pushes it into ground. Two active steering joints and Excavation direction of a direct pipe machine is shown in Fig. 2.

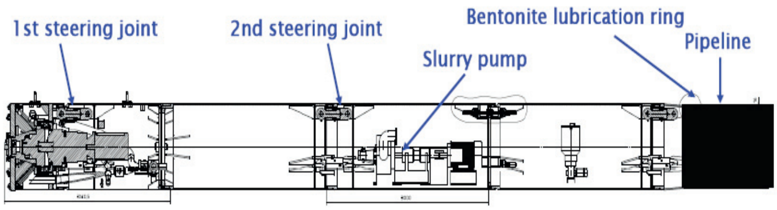

Figure 2. The setup of micro-tunnel boring machine and the steering joints

Herrenknetch universal navigation system is used to monitor direction of the Direct Pipe during excavation. A hydrostatic water leveling system gives vertical orientation of machine. Maximum height difference of ±3 to 15 mm can occur. Gyro compass is used to determine horizontal direction of the Direct Pipe machine. Horizontal deviations of maximum ±5 cm can be seen. The deviations are very small as compared to HDD method in which deviation of few meters is observed. This small deviation helps to get to the target point accurately. Rear end of the Direct Pipe machine is conical in shape. This increases annular gap between pipe and surrounding ground. Lubrication ring is attached to the Direct Pipe machine in rear portion of conical shape. Bentonite lubrication is injected into the gap so as to minimize friction when pushing pipe into ground. The cutting head is attached to front side of the Direct Pipe machine. When thruster applies thrust and bentonite is supplied by feed line then the cutting head will start excavation.

Individual pipes which are stored in the storage yard are welded together to form desired section of pipe for thrusting. The length of section depends upon space availability. Once welding is finished then feed line, slurry line, electrical line, data cable, air and bentonite lubrication lines are installed. Then cranes will lift the section and place it on roller. Pipe section is then welded to rear end of the Direct Pipe machine and then it is ready for excavation.

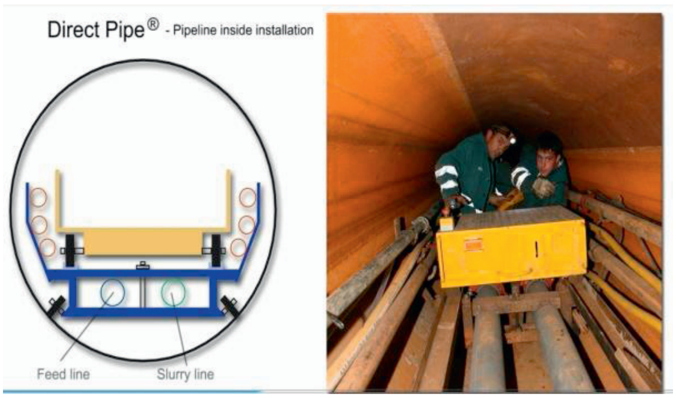

Figure 3. Installation lines in the pipe

Fig.3 shows a section of pipe showing various installation lines and crew surveying pipe.Before staring excavation tanks must be checked to see if they are full of lubricants or not. Direct pipe machine starts excavation. Pushing for required for excavation is transferred to cutting head by thruster. At the same time lubrication is supplied through feed line which facilitates excavation process. Thus, cutting head excavate along predetermined alignment installing pipeline. As soon as the direct pipe machine reaches target pit then the direct pipe machine is lifted up and pipe become ready for further use. Thus product pipe can be installed in this way. Next section will describe briefly data collection process and characteristics of three projects where the direct pipe technology is implemented.

3. Model Development

The CYCLONE model is developed based on guideline developed by Halpin and Riggs(Halpin, 1992). The *Directpipe* technology is combination of the HDD and microtunneling so the CYCLONE model is developed based on the research conducted by Luo R. and Najafi M (Luo and Najafi, 2007), and Nido (1999). The CYCLONE model is modified to represent CYCLONE model of the direct pipe trenchless technology operations.

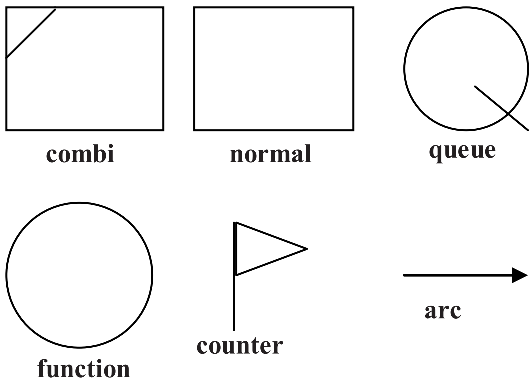

Figure 4. Cyclone modelling elements

The CYCLONE model is normally developed in three steps i.e. Identification of resources, Identification of flow unit cycles and integration of flow unit cycles but here due to complexities of model and to make it easy to understand first two steps are combined into one and thus model is developed in two steps.

The basic modelling elements used in the CYCLONE methodology are shown in Fig. 4.These elements are described as follows: combi (COMBI), represents a work task constrained by one or more resources; counter (COU), keeps track of the number of times a unit passes it; function (FUN), simulation entities can be accumulated at this node; normal (NORMAL), represents a non-constraint work task with an infinite number of servers; queue (QUE), a node where idle resources wait and is always followed by COMBI nodes; arc indicates the logical structure of model and direction of entity flow (Halpin, 1992). All the complete modelling elements for *Directpipe* technology are shown on Table 1 – 5.

Major resources are those for which time duration available and most importantly without which the direct pipe process doesn't start and the resources on which process is not directly depend but are important because their presence activates other necessary activities which are helpful for starting process. The major or primary resources are The pipe sections, The Pipe thruster, Two laborer crews (crew A & crew B), The lubrication mixture, Water in the spoil removal tank that is removed from borehole. Other resources are identified as secondary resources which are enlisted as follows Backhoe, Crane, Dump trucks, Air grippers, Mix of bentonite slurry and polymer additives.

3.1. Main resources

The pipe section is one of the major resources. Truck will deliver pipes to site and it will be unloaded in storage area. Crew A will roll the pipe to base of crane whenever required. Then feed line, slurry line, air hoses and data cables, electricity cables are installed inside pipes. Then four individual pipes are welded together to form a single pipe section of approximately 50 m. We assumed that due to space constraints only 50 m length of pipe can be installed and thrusted at a time. Once the Pipes are welded then Cranes will lift the pipe section of 50 m and place them on guardrail. Crew B willsetup pipe for installation. Crew B carries setup activities such as connecting slurry pipes, air hoses and cables, and placing lubrication ring in rear conical section of the direct pipe machine. After setup is finished it is ready for thrusting. After arriving direct pipe machine at launch pit the machine can be lifted up and all lines i.e. feed, slurry, air hoses and data cables, electricity cables are then removed and thus one cycle of pipe is completed.

The pipe thruster will be brought into action as soon as pipe section is setup on the guardrail and connected to rear end of the direct pipe machine. Whole connection is checked and lubrication tanks are checked to ensure whether they are full of lubricants or not. Once check is done and everything seems right then Pipe thrusting process begins. Thus one cycle of thruster consist of thruster thrusting pipe section and returning back to idle state.

Table 1. NORMAL elements in *Directpipe* model

Element number	Description
6	Dummy
14	Lift to guard rail
20	Crane returns
23	Thrust pipes

Here we assumed that crew A consists of six laborers. We need the crew for rolling pipe under each crane and then installing pipe and welding pipe. As we have chosen 50m length of pipe which is big due to this fact we assumed that six laborers are used. The crew A will be assigned to various tasks. We assumed here that the crew doesn't interact with the Pipe thruster this assumption avoid any interference of crews. So any activity related to pipe thrusting is carried out by crew B. Crew A will be involved in carrying out welding of pipes, rolling pipe sections under crane, Carrying out necessary installation such as slurry line, feed line, electricity, data cable etc. It will also be involved in mixing lubrication fluids. We assumed crew B of four workers. The crew is involved pipe thrusting related activities. Out of these it has one technician and along with remaining three workers the crew will dismantle slurry and spoil lines as soon as the direct pipe machine reaches target pit. The crew is also involved in slurry recycling equipment activity.

The lubrication cycle starts with lubrication present in the storage tank and ready for use on site. The lubrication must be available during connecting pipe section to rear end of the direct pipe machine. It will be injected into lubrication ring. Lubrication is also required through whole thrusting process until slurry lines and feed lines are dismantled. Spoil is removed through slurry discharge lines during thrusting process. It is then separated from the slurry and dumped into the storage tank before it is loaded into dump trucks for hauling to disposal sites. Flow unit of process assumed to be one.

Slurry is needed and must be available. It must be available during all phases of thrusting. During thrusting process spoil is removed through slurry returns lines in form of slurry suspension. Then spoil is separated from slurry by using separation unit. Where spoil settles down and overflowing water is collected in front chamber. Stored slurry in rear chamber is then dumped by using dump trucks. Flow unit is filling one spoil tank.

3.2. Model Development and Integration

Cycles of major resources along with secondary resources cycle are integrated and final direct pipe simulation model is develop which is shown in **Appendix 1**. Some assumptions are made in developing the CYCLONE model for the Direct Pipe technology. The assumptions are described as follows

a. Initially it is assumed that all pipe sections are on the storage area and In launching pit only the thruster and MTBM machine is present. All resources are initialized by considering this assumption.

b. A Pipe thruster, guard rail and MTBM are pre-installed on the project.

c. The project has homogeneous soil thus avoiding need of incorporating any probabilistic option thus making model less complex.

d. One production cycle is finished after one pipe section (consist of four pipe strings) of 200m length is thrusted into ground. After reaching launching pit cables, slurry lines, feed lines etc are uninstalled.

e. Pipe connection is carried out after four sections have been ready and it is assumed that 33% of time it is adjusted.

f. Any delay caused due to breakdown of the direct pipe machine and any occurrences of unforeseen obstructions are not considered.

One full tank of lubrications lasts until a pipe section (4 pipes) is thrusted. Also spoil tank emptied after thrusting a pipe section (4 pipes) and water in system changed after thrusting for a pipe section (4 pipes).

Table 2. QUEUE elements in *Directpipe*model.

Element number	Description	Gen	Qua	Resource Type
1	Pipes in site storage	-	12	Pipes
4	Needs connector	-	-	-
7	Crew A idle	-	6	Crew A
8	Needs check connection	-	-	-
10	Connection ready	4	1	Connection
11	Position occupied	-	-	-
12	Position available	-	1	Position
15	Pipe section ready to thruster	-	-	-
17	Pipe section ready to installation	-	-	-
19	Crew B idle	-	4	Crew B
21	Crane idle	-	3	Crane
25	Needs lubricants	-	-	-
27	Bentonite ready	-	1	Bentonite
28	Lubricants ready	4	1	Lubricants
30	Spoil tank full	-	-	-
32	Backhoe ready	-	1	Backhoe
33	Truck ready	-	1	Truck
34	Spoil tank not full	4	1	Spoil tank
35	Pipes in distance	-	-	-
37	Control room to command	-	1	Remote control room
38	Thruster ready	-	1	Thruster
40	Slurry needs recycle	-	-	-
42	Water ready	4	1	Water
43	Cable and hose ready	-	1	Cable and hose

Table 3. FUNCTION elements in *Directpipe* model

Element number	Description	Consolidate
3	CON 4	4
24	CON 4	4
29	CON 4	4
39	CON 4	4
44	COU	-

Table 4. Duration used for Simulation model
(adopted from Luo R. and Najafi M. 2007)

Element number	Description	Distribution
2	Bring pipes to connecting	TRI (2, 5, 15)
5	Connect / weld pipes	UNI (10, 15)
9	Check pipes connection/welding	UNI (10, 15)
13	Attach pipes to crane	DET (2)
16	Roll pipes to thruster machine	UNI (1, 2)
18	Pipes setup/installation	BETA (28, 80, 0.761, 1.841)
26	Mix lubricants	TRI (25, 30, 35)
31	Empty spoil tank	TRI (20, 30, 35)
36	Uninstall cable/hose/UNS	BETA (7, 33, 0.643, 3.020)
41	Recycle slurry	TRI (10, 12, 15)
6	Dummy	DET (0)
14	Lift to guard rail	DET (1)
20	Crane returns	DET (2)
23	Thrust pipes	DET (40)

Table 5. Resource cost information (adopted from Luo R. and Najafi M. 2007)

Resource	Costs ($)
Pipes	5600/section
Crew A	44/hr
Crew B	40.8/hr
Crane (+ operator)	61.45/hr
Thruster system	550/hr
Backhoe (+ operator)	27.9/hr
Truck	51/hr
Water	17
Bentonite	21.6
Lubricants	28

4. Results and Discussion

4.1. Productivity Analysis

By using HDD method product pipe of larger diameter cannot be installed in contrast to the direct pipe technology. This will make it difficult to compare costs but still an inadequate comparison can gives us some reliable information.

As per “An Industry Survey of Horizontal Directional Drilling in North America” by Carpenter [6], the maximum cost of installation by HDD varies with product pipe diameter. Maximum cost of installation is observed while installing product pipe maximum diameter (diameter = 300 mm). Maximum average cost of installing HDD pipe is $252/L.M. On the other hand by simulation cost of installing the direct pipe technology for 48” steel pipe diameter is $5706/L.M.

Hence cost of installation by the direct pipe method is much higher than the HDD method. In conclusion; HDD must be used for installation of product pipe whose diameter is equal to or less than 300 mm (diameter ≤ 300) and the direct pipe machine must be used in case of installation of product pipe whose diameter is higher and which can't be installed by using the HDD technology. In some cases especially when depth of cutting is more and geological conditions are adverse for the HDD method in that situation the direct pipe technology is used to install product pipe of either smaller or larger diameter.

The maximum productivity of HDD can be obtained in case of drilling in clay and silt clay. It is very difficult to compare productivity with the direct pipe technology but still smallest average productivity and highest average productivity of HDD method can be calculated and compared to reach few conclusions. The maximum productivity per day for different kinds of soils and product diameter in range of 50-100mm (small) are as shown in Table 6.

Table 6. Average Productivity (L.M. /day) in Various Subsurface Formations (dia- 50-100mm)

Soil Type	Average productivity
Clay	180
Silty- Clay	221
Sand	133
Gravel	80
Cobbles	38
Hard Pan	95
Sandstone	149
Bedrock	103

A total of 12 cycles simulated by using the Cyclone showedthat the productivity per unit time is 0.189497758 for total simulation of 1266.5 time unit. It gives productivity rate 11.36 meter/hour**.**Considering the costs, achieved productivity rate is $5706/m. The maximum average productivity is 124.875/day or 15.61 L.M. /hr (assuming 8hrs/day). Productivity of the direct pipe technology obtained by simulation is 11.36 L.M/hr

4.2. Sensitivity Analysis

Sensitivity analysis is carried out in order to find out effect of variation in management controlled variable i.e. resources on productivity and cost of installation(Woodroof and Ariaratman, 2008). Resources such as Crew A, Crew B, crane, truck, backhoe, lubricants and water are varied in their numbers and results obtained are shown in Table 7 – 9.

Table 7. Sensitivity analysis for number of crew

Resource Information	Productivity Information		
# of CREW A	Productivity Per Unit Time	Cost Per Unit Time	Cost Per Prod. Unit
1	0.1943	1160	5975
2	0.2040	1162	5694
3	0.1909	1142	5982
4	**0.2069**	**1179**	**5701**
5	0.1919	1149	5990
# of CREW B	Productivity Per Unit Time	Cost Per Unit Time	Cost Per Prod. Unit
1	0.1841	1154	6268
2	0.1884	1181	6272
3	0.1861	1168	6276
4	**0.1944**	**1165**	**5994**
5	0.1838	1155	6283

Table 8. Sensitivity analysis for number of Backhoe and Truck

# of BACKHOE	# of TRUCK	Productivity Per Unit Time	Cost Per Unit Time	Cost Per Prod. Unit
1	**1**	**0.1983**	**1188**	**5994**
1	2	0.1964	1178	5998
2	1	0.1917	1149	5996
2	2	0.1826	1147	6287

Table 9. Sensitivity analysis for number of crane

# of CRANE	Productivity Per Unit Time	Cost Per Unit Time	Cost Per Prod. Unit
1	0.1896	1188.2273	6268
2	**0.1976**	**1183.2629**	**5988**
3	0.1855	1165.2155	6279

The productivity per unit time can be increase in following situations so as to achieve maximum productivity and reduce cost.

a. Changing number of Crew A from 6 to 4.
b. Keeping number of Crew B to 4.
c. Providing only one backhoe.
d. Changing the number of crane from 3 to 2 units.
e. Increasing number of water and lubricants (6 sections and 5 sections respectively.

5. Conclusion

Advantages of the direct pipe technology over trenchless technologies are briefly presented as follows:

a. Low drilling time and high performance rate can be achieved due to continuous pipe jacking. Pipe thruster force and advantage of installing large pipe sections helps to achieve maximum performance rate.

b. Pipes of large diameter can be laid without using casing pipes.

c. Product pipe can be laid in only one step in contrast to conventional trenchless technologies.
d. Risk of failure due to subsoil condition is minimized by providing permanent drill hole support thus disadvantage of HDD i.e. drill hole collapse is removed.
e. The technology can be used in any geological condition due to adaptability of cutting wheel and cutting tool to any geological conditions.
f. Deposits in borehole are impossible because crushed rocks can be removed through supply lines.
g. Conventional method requires large space either on launch side or target side but in case of the direct pipe technology minimum space is required on only launch side.

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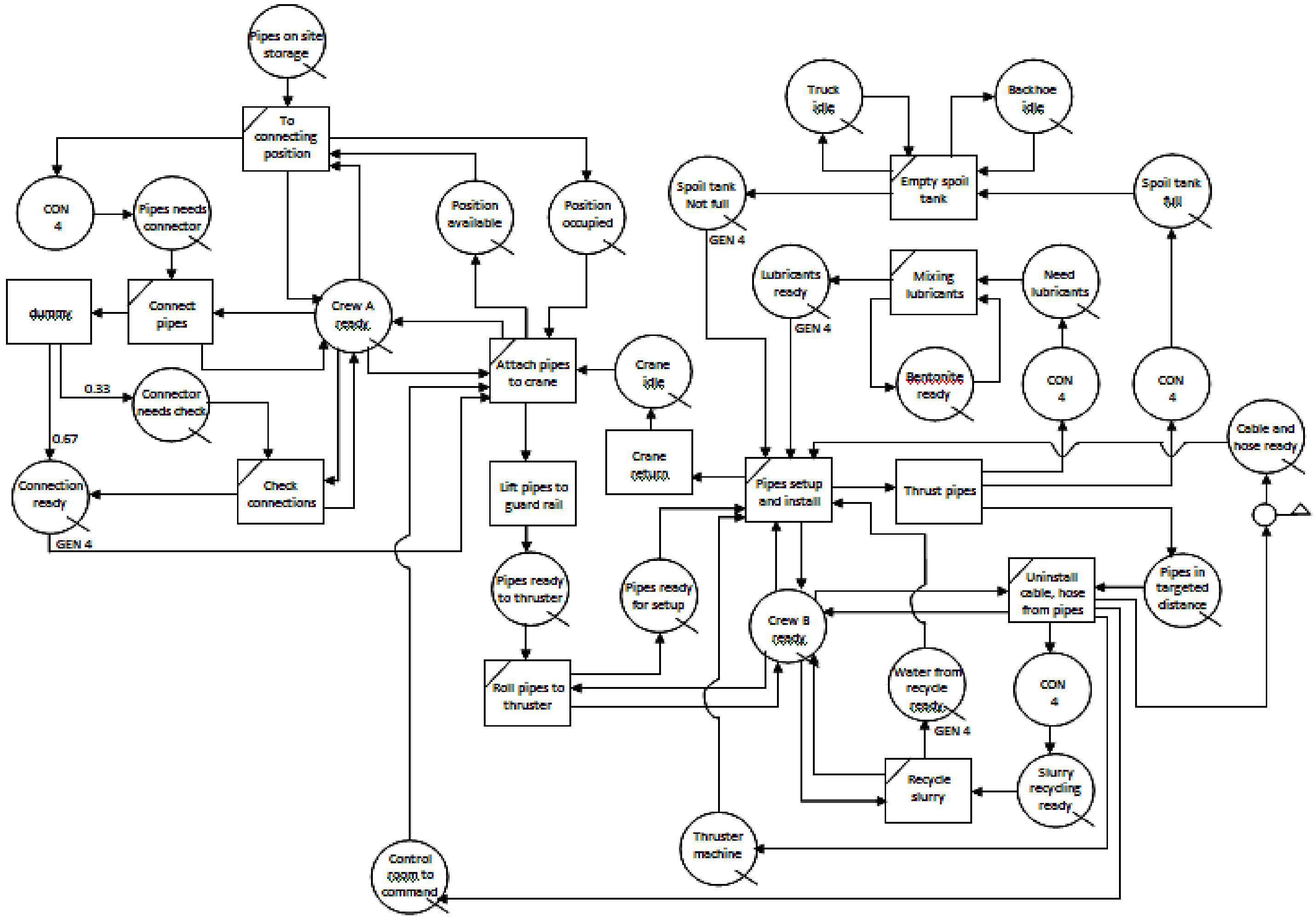
APPENDIX 1 – CYCLONE MODEL FOR DIRECTPIPE TECHNOLOGY



APPENDIX 2 – OVERALL PROCESS OF DIRECTPIPE TECHNOLOGY